SCIENCE FOR GLASS PRODUCTION

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UNDULATING DEFORMATION OF SHEET GLASS IN HORIZONTAL HARDENING

A. I. Shutov,[1] A. S. Ostapko,[1] and A. N. Frank[1]

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An algorithm for the calculation of undulating deformation in sheet glass under horizontal hardening has been developed, which is fundamentally different from those previously proposed. A minimum glass transportation velocity is calculated, which corresponds to the maximum admissible deformation of glass. This algorithm is recommended for use in designing production lines for horizontal hardening of glass.

Horizontal hardening is currently the most advanced method for strengthening sheet glass, which, apart from significant advantages, has an important disadvantage, i.e., undulating deformation of the glass sheet due to deflection of the glass sheet and flanging of its edges caused by the high temperature of the product.

Previous calculations [1] allowed a conclusion regarding the qualitative and quantitative effect of the rotational speed of the conveyor rollers, initial temperature of glass hardening, and glass thickness on the degree of undulating deformation of glass during heat treatment.

It is known [2] that residual hardening stress in glass is a consequence both of thermal deformation and of structural modifications occurring during the whole process and depends on glass viscosity.

The algorithm described in [1] calculates the temperature dependence of glass viscosity in accordance with the Tamman – Fulcher equation:

$$\log \eta = A' + \frac{B'}{t - C},$$

where t is the glass sheet temperature; A', B', and C are constants.

To determine A', B', and t_0, at least three pairs of values $\eta(t)$ are required.

However, in the opinion of Andrade [3], in the range of high temperatures and sufficiently low viscosity values one should apply the Arrhenius equation:

$$\log \eta = A'' + B''/t,$$

where A'' and B'' are constants.

[1] Belgorod State Technological Academy of Construction Materials, Belgorod, Russia.

The viscosity of glass in the expected technological range can be calculated as follows:

$$\eta = e^{A' + \frac{B'}{t - C}} \quad \text{for } \log \eta \geq 9;$$

$$\eta = 10^{A'' + \frac{B''}{t}} \quad \text{for } \log \eta < 9.$$

The dependence of glass deformation on its thickness, viscosity, and speed of the roll conveyor given in [1] has the form

$$y = \frac{3}{2} \frac{E(t_0) l^5 \rho g}{E_0 \eta(t_0)(1 + \mu) d^2 v}, \quad (1)$$

where $E(t_0)$ and E_0 is the Young's modulus of glass at the hardening t_0 and room temperatures; l is the spacing between rollers; ρ is the glass density; g is the free fall acceleration; $\eta(t_0)$ is the viscosity of glass at the hardening temperature; μ is the Poisson coefficient; d is the glass thickness; v is the velocity of glass moving over the roller conveyor.

The undulating deformation value is experimentally estimated using the optical distortion angle α_{opt} of articles determined according to GOST 5727–88 employing a Zebra set.

The following relationship earlier established [4]:

$$\alpha_{opt} = S_{opt} \, y^{-1},$$

where S_{opt} is the optical transition modulus, did not fully correspond to reality, whereas the formula described in [1] has a narrow application area for determining the optical distortion

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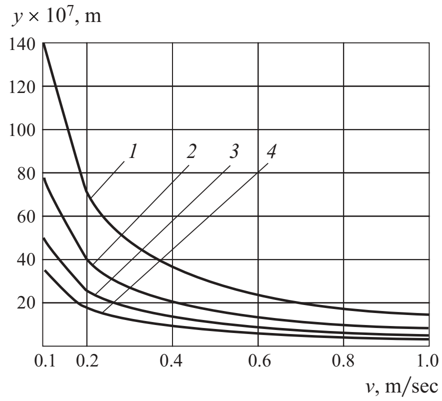

Fig. 1. Dependence of undulating formation in sheet glass on conveyor velocity for glass of thickness 3 (*1*), 4 (*2*), 5 (*3*), and 6 mm (*4*).

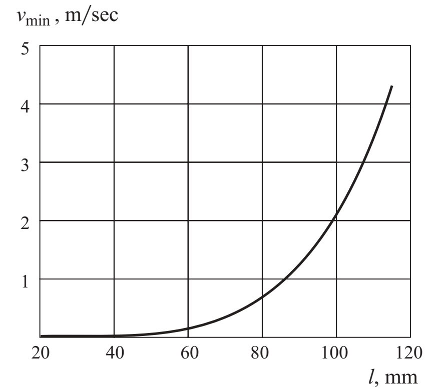

Fig. 2. Dependence of the minimum required velocity of transportation of sheet glass 3 mm thick hardened at 640°C on spacing between the conveyor roller.

angle, since interpolation was performed only for specific heat treatment conditions, namely, $l = 80$ mm and $t_0 = 640$°C:

$$\alpha_{opt} = \frac{l}{225 \times 10^{-2} - \frac{5.51 \times 10^{-4} - 7.968 \times 10^{-5} d}{v^2} \ln(v)} . \quad (2)$$

Thus, the algorithms proposed earlier had no adequate correlation between α_{opt} and heat treatment parameters.

Evidently the optical distortion angle depends only on deformation, and the ultimate deformation value y_{min} corresponding to glass with optimum properties will be different in glasses of different thickness. Consequently, having determined the values y_{min} for each glass thickness, it is possible to calculate the minimum required velocity using expression (1).

In order to determine y_{min}, let us calculate the velocity using formula (1) and substitute it in Eq. (2) taking $\alpha_{opt} = 44°$.

Taking into account the restrictions imposed earlier on Eq. (2) ($l = 80$ mm, $t_0 = 640$°C), we will solve this equation using numerical methods for each thickness of glass. The results obtained are listed below:

***d*, mm**	**$y_{min} \times 10^6$, m**
3	1.9925
4	1.1958
5	0.8485
6	0.7223

Thus, based on formula (1):

$$v_{min} = \frac{3}{2} \frac{E(t_0) l^5 \rho g}{E_0 \eta(t_0)(1+\mu) d^2 y_{min}} .$$

Figure 1 represents the dependence of undulating deformation of glass on the velocity of its motion on the roller conveyor at temperature $t_0 = 640$°C and $l = 80$ mm for different thicknesses of glass. It can be seen that thick glass is the least sensitive to deformation.

Unlike other methods described earlier [1, 4], this algorithm makes it possible not only to calculate the minimum required velocity for glass moving on the roller conveyor at a preset temperature t_0 and preset thickness, but also to estimate minimum velocity values taking into account the spacing between the rollers and the maximum admissible deformation of sheet glass (Fig. 2).

The use of the method proposed makes it possible to refine previous calculations [1] and to determine the minimum required velocity that would correlate with the maximum admissible deformation of sheet glass, i.e., to obtain objective data in designing new horizontal hardening lines and upgrading existing lines.

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